APPARATUS AND METHOD FOR CONVERTING ANALOG SIGNAL TO PULSE-WIDTH-MODULATED SIGNAL

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to oversampled, noise-shaping signal processing circuits, and in particular, to noise-shaped, high-efficiency amplifiers which convert an analog input signal to a pulse-width-modulated output signal.

2. Description of the Related Art

Referring to Figure 1, a conventional high-efficiency amplifier system 10 includes, in various forms, a modulator 12, an amplifier 14 and a filter 16, interconnected substantially as shown. The analog input signal 11 is modulated by the modulator 12 and the modulated signal 13 is amplified by the amplifier 14 which is typically a switching circuit so as to maintain high-efficiency. The amplified signal 15 is filtered by the filter 16 to produce the desired analog output signal 17. The amplifier 14 is a switching amplifier so as to minimize power dissipation, thereby allowing the modulator 12 and amplifier 14 to be integrated within a single integrated circuit 18.

One problem associated with such a system 10 is that of power supply ripple being coupled into the output signal 17 through the amplifier 14. Accordingly, techniques are needed to increase power supply rejection, particularly when using switching amplifiers.

Referring to Figure 2, one technique involves noise shaping the output signal spectrum. This is done by feeding back the output signal 15 from the amplifier 14 via a feedback network 22. The resulting feedback signal 23 is then differentially summed with the input signal 11 in a signal summer 24. The resulting sum signal 25 is modulated by the modulator 12, rather than the original input signal 11.

Alternatively, the filtered output signal 17 from the filter 16 can be fed back instead of the non-filtered signal 15. However, the problem associated with

feeding back the filtered output signal 17 is the difficulty in creating a system which is stable and still has a high gain and wide bandwidth. This problem arises due to the fact that the filter 16 is typically a second order filter with a natural, or cutoff, frequency which is just outside the bandwidth of interest. The two poles associated with this filter 16 restrict the open loop unity crossover bandwidth of the overall loop to the cutoff frequency, which is approximately the signal bandwidth. This means that the in-band gain cannot be very large. As a result, suppression of power supply ripple, switching noise and other undesirable in-band signals is generally minimal.

On the other hand, feeding back the non-filtered signal 15, *i.e.*, directly from the switching node output of the amplifier 14, the amount of feedback (*i.e.*, with respect to gain and bandwidth) is less restricted thereby making it possible to use more sophisticated feedback techniques, such as noise shaping. Noise shaping techniques, sometimes referred to as delta-sigma techniques, allow for the selective reduction of quantization noise present at the switching output of the high-efficiency amplifier stage 14.

Referring to Figure 3, a conventional delta-sigma loop includes a serial configuration of integrators 32, 34, quantizer 36, amplifier 38, feedback network 40 and signal summing stages 42, 44 interconnected in a loop substantially as shown. (This delta-sigma loop configuration is illustrated as a second order configuration, but it will be readily understood that the techniques discussed herein can be scaled as desired to higher order loop configurations as well.) The feedback network 40 can implement various forms of feedback techniques.

For example, when the amplifier output 39 is to be fed back, and such output 39 is an analog signal, the feedback network 40 may include filtering when sampled integrators 32, 34 are used. Alternatively, if the integrators 32, 34 are continuous time integrators, the feedback network 40 need not necessarily include filtering, but may provide only continuous time gain as needed for the feedback signals 41a, 41b. Alternatively, if the quantizer output 37 is to be fed back, the feedback network 40 may include discrete time feedback, such as a digital-to-analog conversion function, so as to provide appropriate analog feedback

signals 41a, 41b. Various combinations and permutations of these types of feedback for continuous time and sampled integrators are discussed in more detail in U.S. Patent No. 5,777,512, the disclosure of which is incorporated herein by reference.

Problems associated with conventional noise-shaped, high-efficiency amplifiers, such as those discussed above, have involved the choice between providing a pulse density modulated (PDM) signal or a continuous pulse-width modulated (PWM) signal as the output. If a PDM signal is used, the resulting output signal has low distortion levels, but contains a high amount of in-band signal noise. Conversely, a continuous PWM signal has less in-band signal noise, but a higher degree of signal distortion. Accordingly, it would be desirable to provide a noise-shaped, high-efficiency amplifier system with less in-band signal noise than a PDM system and less signal distortion than a continuous PWM system.

SUMMARY OF THE INVENTION

A circuit for converting an analog signal to a pulse-width-modulated (PWM) signal uses noise shaping techniques, such as a delta-sigma amplifier, along with a discrete PWM stage to produce a discrete PWM output signal having lower in-band signal noise than a PDM system and a lower signal distortion than a continuous PWM system. Additionally, a multiple bit quantization stage can be used to drive the discrete PWM stage.

An apparatus including a circuit for converting an analog signal to a pulse-width-modulated signal in accordance with one embodiment of the present invention includes an integration stage, a modulation stage and a feedback stage. The integration stage is configured to receive, combine and integrate an analog input signal and a set of one or more feedback signals and in accordance therewith provide a set of one or more integrated signals. The modulation stage, coupled to the integration stage, is configured to receive and modulate a final portion of the set of one or more integrated signals and in accordance therewith provide a discrete time pulse width modulated signal The feedback stage, coupled between

the modulation stage and the integration stage, is configured to receive the discrete pulse width modulated signal and in accordance therewith provide a portion of the set of one or more feedback signals.

An apparatus including a circuit for converting an analog signal to a pulse-width-modulated signal in accordance with another embodiment of the present invention includes:

integration means for receiving, combining and integrating an analog input signal and a set of one or more feedback signals and in accordance therewith providing a set of one or more integrated signals;

modulation means for receiving and modulating a final portion of said set of one or more integrated signals and in accordance therewith providing a discrete time pulse width modulated signal; and

feedback means for receiving the discrete time pulse width modulated signal and in accordance therewith providing a portion of the set of one or more feedback signals.

A method for converting an analog signal to a pulse-width-modulated signal in accordance with another embodiment of the present invention includes the steps of:

receiving, combining and integrating an analog input signal and a set of one or more feedback signals and in accordance therewith generating a set of one or more integrated signals;

generating a discrete time pulse width modulated signal in accordance with said set of one or more integrated signals; and

feeding back the discrete time pulse width modulated signal as a first portion of the set of one or more feedback signals.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a functional block diagram of a conventional high-efficiency switching amplifier system.

Figure 2 is a functional block diagram of a conventional high-efficiency switching amplifier system using feedback for noise shaping.

Figure 3 is a functional block diagram of a conventional high-efficiency switching amplifier system using delta-sigma noise shaping techniques.

Figure 4 is a functional block diagram of a high-efficiency switching amplifier system using noise shaping techniques in accordance with one embodiment of the present invention.

Figure 5 is a functional block diagram of a high-efficiency switching amplifier system using noise shaping techniques in accordance with another embodiment of the present invention.

DETAIL DESCRIPTION OF THE INVENTION

Referring to Figure 4, a high-efficiency switching amplifier system 100 using noise shaping techniques in accordance with one embodiment of the present invention includes serially coupled integrators 102, 104, a quantizer 106, a discrete pulse-width modulator 108, a feedback network 110 and signal summers 112, 114, interconnected in a closed loop configuration substantially as shown. The input analog signal 101 is alternately summed with feedback signals 111a, 111b in the signal summers 112, 114 and integrated by the integrators 102, 104, in accordance with well-known delta-sigma techniques. (A second order delta-sigma configuration is shown and discussed herein, but it will be readily understood that higher order delta-sigma techniques can also be used in accordance with the present invention.) The resulting signal 105 is then quantized in a multiple-bit quantizer stage 106, and the multi-bit quantized signal 107 is converted to a discrete time PWM signal 109 by the discrete pulse-width modulator stage 108. This output signal 109 is an analog signal which is then fed back through the feedback network 110 to produce the feedback signals 111a, 111b used by the delta-sigma section.

In accordance with well-known techniques, the feedback network 110 can provide either continuous time feedback or discrete time feedback depending upon the nature of the integrators 102, 104. For example, if the integrators 102, 104 are continuous time integrators which inherently accept low frequencies and reject high frequencies, the feedback network 110 can merely provide continuous time

gain as needed. Alternatively, if the integrators 102, 104 are sampled integrators, the feedback network 110 will provide anti-alias filtering (*e.g.*, lowpass filtering for baseband feedback signals or bandpass filtering for feedback signals which are not baseband), plus continuous time gain as needed. (Various combinations and permutations of continuous time and discrete time feedback networks used with continuous time and sampled integrators are discussed in more detail in the aforementioned U.S. Patent No. 5,777,512, the disclosure of which is incorporated herein by reference.) Further alternatively, the input analog signal 101 can be fed forward via a feed forward stage 116 (e.g., with signal gain or filtering characteristics as desired) with the resultant signal 117 then being summed with integrated signal 103 and feedback signal 111b. (Other possible combinations and permutations of feed forward configurations for the input signal and various ones of the integrated signals will be readily apparent to one of ordinary skill in such art.)

With respect to the quantizer 106 and discrete pulse-width modulator 108, it will be readily understood that, in accordance with well-known techniques, these elements can also be "merged" into a single functional unit. For example, an analog-to-discrete-time-pulse-width modulation conversion can be performed in such a manner that no multi-bit quantized signal 107 need be generated.

Referring to Figure 5, an alternative system 200 in accordance with another embodiment of the present invention provides more discrete feedback paths. Feedback network 110 provides feedback for the discrete time PWM signal 109, as discussed above, while another feedback network 120 creates a minor feedback loop by feeding back the multibit quantized signal 107. In accordance with one embodiment, the major loop feedback network 110 is a continuous time feedback network for feeding back the analog discrete time PWM signal 109, while the minor loop feedback network 120 is a discrete time feedback network (*e.g.*, a digital-to-analog conversion circuit) for feeding back the multi-bit digital quantized signal 107.

Based upon the foregoing, it can be seen that a noise-shaped, high-efficiency amplifier system in accordance with the present invention provides some of the advantages associated with continuous pulse-width modulation (low

noise) while also providing some of the advantages associated with pulse density modulation (high linearity). Furthermore, multiple bit quantization is provided, thereby providing for a greater degree of inherent stability of the delta-sigma modulator. Hence, such a system is as close to PDM as possible while still maintaining a desirable degree of stability within the system.

Various other modifications and alterations in the structure and method of operation of this invention will be apparent to those skilled in the art without departing from the scope and spirit of the invention. Although the invention has been described in connection with specific preferred embodiments, it should be understood that the invention as claimed should not be unduly limited to such specific embodiments. It is intended that the following claims define the scope of the present invention and that structures and methods within the scope of these claims and their equivalents be covered thereby.